U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-297 036

Areawide Waste Treatment and Water Quality Management Planning. Appendix C-2. Geology of the Coal-Mining Portion of the Southern Illinois 208 Area and Its Application to Water Quality Problems

Greater Egypt Regional Planning and Development Commission, Carbondale, IL

Prepared for

Environmental Protection Agency, Chicago, IL. Region V

Nov 78

PB 297036

Areawide Waste Treatment and Water Quality Management Planning

Geology of the Coal-Mining Portion of the Southern Illinois 208 Area and Its Application to Water Quality Problems

Appendix C-2

Franklin, Gallatin, Hamilton, Hardin, Jackson, Jefferson, Perry, Pope, Saline, and Williamson Counties, Illinois

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

GREATER EGYPT REGIONAL PLANNING & DEVELOPMENT COMMISSION

Areawide Waste Treatment and Water Quality Management Planning

5

Geology of the Coal-Mining Portion of the Southern Illinois 208 Area and Its Application to Water Quality Problems

Appendix C-2

Franklin, Gallatin, Hamilton, Hardin, Jackson, Jefferson, Perry, Pope, Saline, and Williamson Counties, Illinois

The preparation of this report was financed entirely with federal funds from the U.S. Environmental Protection Agency under grant number P005225-01 through a contract with the Greater Egypt Regional Planning and Development Commission. The contents do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. Publication No. GERPDC-78-494.

BIBLIOGRAPHIC DATA SHEET	1. Report No. GERPDC-78-494	2.	3. Recipient's Accession No. PB297036
4. Title and Subtitle Areawide Waste Treatment and Water Quality Management Planning Geology of the Coal-Mining Portion of the Southern Illinois 208 Area and Its Applications to Water Quality Problems, Appendix C-2			5. Report Date November 1978 6.
7. Author(s) William C. Hood, Southern Illinois University-Carbondale			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Greater Egypt Regional Planning and Development Commission P.O. Box 3160 Carbondale, IL 62901			10. Project/Task/Work Unit No. 11. Contract/Grant No. P005225-01
12. Sponsoring Organization Name and Address U.S. Environmental Protection Agency Region V 230 South Dearborn Chicago, IL 60604			13. Type of Report & Period Covered Final 14.

15. Supplementary Notes

16. Abstracts

The Geology of the Coal-Mining Portion of the Southern Illinois 208 Area and Its Applications to Water Quality Problems report is Appendix C-2 of the Areawide Waste Treatment and Water Quality Management Plan for Southern Illinois. The report was prepared under Section 208 of the Water Pollution Control Act, as amended. The report addresses the physiography, topography, structure and stratigraphy of the Southern Illinois 208 area, and their relationship to water quality problems. Included are conclusions and recommendations.

17. Key Words and Document Analysis. 17a. Descriptors

Geology, water pollution.

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
National Technical Information Service U.S. Department of Commerce Springfield, VA 22151	UNCLASSIFIED	62
	20. Security Class (This Page) UNCLASSIFIED	22. Price A04-A01

FORM NTIS-35 (REV. 3-72) THIS FORM MAY BE REPRODUCED USCOMM-DC 14952-P72

GREATER EGYPT REGIONAL PLANNING & DEVELOPMENT COMMISSION

608 east college st. / carbondale, illinois / area code 618 549-3306
mailing address: post office box 3160 / carbondale, illinois / 62901

November 1978

Michael P. Mauzy
Acting Director
Illinois Environmental Protection Agency
2200 Churchill Road
Springfield, Illinois 62706

Dear Mr. Mauzy:

The Commission is pleased to transmit Appendix C-2, Geology of the Coal-Mining Portion of the Southern Illinois 208 Area and Its Applications to Water Quality Problems of the 208 Areawide Waste Treatment and Water Quality Management Plan for Southern Illinois. The plan and this document cover the ten Illinois Counties of Franklin, Gallatin, Hamilton, Hardin, Jackson, Jefferson, Perry, Pope, Saline, and Williamson.

This technical report is an integral part of the Southern Illinois Water Quality Management Plan that is designated to meet the contract requirements of Federal Grant Number P005225-01 under the U. S. Water Pollution Control Act Amendments of 1972, as administered by the United States Environmental Protection Agency.

We trust this submittal of this report, as well as the others comprising the plan, will provide the basis for certification of the plan and continued designation of this area.

Sincerely,

A. S. Kirkikis

A. S. Kirkikis
Executive Director

ASK:db

Prepared Under Contract

For

GREATER EGYPT REGIONAL PLANNING
AND DEVELOPMENT COMMISSION
608 EAST COLLEGE STREET
CARBONDALE, ILLINOIS 62901

By

William C. Hood
Department of Geology
Southern Illinois University
Carbondale, Illinois 62901

III

ACKNOWLEDGEMENTS

The author wishes to thank Cathlee Smith for her assistance in the literature review, and Marcia Killian, Jeanice Bleem, and Stephen McChesney for their assistance in the preparation of the manuscript.

GREATER EGYPT REGIONAL PLANNING AND DEVELOPMENT COMMISSION

Commission Members

Franklin County

R.A. Bonifield
Albert Chiaventone
Russell Davis
George Tomlinson

Jackson County

Osbin Ervin
Bill Kelley
Reginald Stearns
Sharon Kowalzik

Jefferson County

Charles Covington
Paul Dickerson
David Sargent
Carl Baker

Perry County

Dr. Allen Y. Baker
J. Paul McNutt
Gene Schumaier
Victor Provart

Williamson County

William Humphreys
Jo M. Walker
Curtis Palmer
Jack Murray

Assembly of Local Governments

Williams Schettler

Conservancy District

Charles Prather

Municipal Representatives

Herbert Mundell, Benton
Archie Jones, Carbondale
Robert Armstrong, DuQuoin
Robert Butler, Marion
Raymond Baril, Mt. Vernon
Joe Williams, Murphysboro
Jack Woolard, West Frankfort

Executive Committee

Chairman -	Jo M. Walker
1st Vice Chairman -	Reginald Stearns
2nd Vice Chairman -	Archie Jones
3rd Vice Chairman -	J. Paul McNutt
Secretary -	George Tomlinson
Treasurer -	William Humphreys
Immediate Past Chairman -	C.J. Covington

Commission Staff

A. S. Kirkikis - Executive Director
James R. Rush - Director of Special Programs
Christine Svec - Director of Long Range Planning
Ronald Clark - Director of Current Planning
Wayne Martin - Criminal Justice Training Coordinator
Saeed Khan - Engineer
R. Jon Herbert - Planner II
Gary Bankston - Planner II
Joseph Wesselman - Planner I
Ronald Hudson - Planner I
William M. Harris - Planner I
Sharon Yeargin - Planner I
Tom Redmond - Planner I
Rue Gene Starr, Sr. - Manpower Specialist
Jack VanZandt - Evaluation Specialist II
Stephen Knox - Citizens Resource Specialist
Barbara Poston - Research Analyst II
James Dine - Research Analyst I
Nancy O'Connor - Research Analyst I
Margie Mitchell - Administrator II
Diana Chandler - Secretary III
Jean Sparenberg - Secretary II
Marleen Romero - Secretary II
Janet Kent - Planning Technician II
Bob Gerl - Planning Technician II
Wendell Keene - Planning Technician II
Janice Jones - Planning Technician II
Harold Dillard - Planning Technician II
Tom Wierzba - Intern

SOUTHEASTERN ILLINOIS REGIONAL PLANNING AND DEVELOPMENT COMMISSION

Commission Members

Gallatin County

William Lawler
Tom Harmon
Stanley Sisk
Delbert York

Hamilton County

Ernest Hood
C. H. McGill
James Mick
Dwight Miller

Hardin County

Donald Austin
Winfred Barnard
Dayton Pearce
Walter Bayne

Pope County

Herman Adkerson
Ralph Aly
Milton Baker
Victor English

Saline County

Harry Hines
Fred Lloyd
Ray Harbison
Art Debes

Executive Committee

Chairman - Ralph Aly
1st Vice Chairman - Fred Lloyd
2nd Vice Chairman - Inman Wheeler
Secretary - Winfred Barnard
Treasurer - William Lawler

Commission Staff

Eric Pflanz - Acting Executive Director
Lu Ann Walker - Economic Development Director
Bonita Stanley - Manpower Planner
Pam Peckler - Health Coordinator
Judy Clark - Administrative Assistant/Bookkeeper
Jackie Walker - Secretary
Verba Elam - Clerical Assistant

LIST OF TABLES

Table		Page
1	Limestone Content and Equivalent Amount of Sulphur That Can Be Neutralized in Pennsylvanian Formations of Illinois	37
2	Average Sulphur Values and Estimated Net Neutralization Potential for Some Southern Illinois 208 Area Mines	38
3	Percent of Various Formations in the Second Order Basins, Southern Illinois 208 Coal Mining Area	41
4	Average Net Neutralization Potential of Some Overburden Rocks in the Southern Illinois 208 Area	44

LIST OF FIGURES

Figure		Page
1	The Southern Illinois 208 Project Area	2
2	Natural Regions of Southern Illinois	4
3	The Eastern Interior Basin in Illinois, Indiana and Kentucky	8
4	Major Structural Features of the Southern Illinois 208 Area	9
5	Stratigraphic Column of the Caseyville, Abbott and Spoon Formations	15
6	Stratigraphic Column of the Carbondale Formation	19
7	Stratigraphic Column of the Modesto, Bond and Spoon Formations	26
8	Areas Covered by Late Pleistocene Glacial Lakes in the Southern Illinois 208 Area	29

TABLE OF CONTENTS

	Page
Chapter 1 - INTRODUCTION	1
Chapter 2 - PHYSIOGRAPHY AND TOPOGRAPHY	3
Chapter 3 - STRUCTURE	7
Fairfield Basin	7
DuQuoin Monocline	7
Eagle Valley Syncline	10
Omaha Dome	10
Hicks Dome	10
Shawneetown Fault Zone	11
Cottage Grove Fault System	11
Wabash Valley Fault System	11
Fluorspar Area Fault Complex	12
Chapter 4 - STRATIGRAPHY	13
Caseyville Formation	14
Abbott Formation	16
Spoon Formation	16
Carbondale Formation	18
Modesto Formation	25
Bond Formation	27
Mattoon Formation	27
Equality Formation	28
Chapter 5 - APPLICATIONS TO WATER QUALITY PROBLEMS	31
The Net Neutralization - pH Relationship	34
General Evaluation	36
Chapter 6 - CONCLUSIONS AND RECOMMENDATIONS	47
REFERENCES	49

LIST OF FIGURES (CONT'D)

Figure		Page
9	Experimentally Established Relationship Between pH and Net Neutralization Potential	35
10	Kosanke et al. (1960) Estimation of the Distribution of Lithologies in Pennsylvanian Formations in Illinois . .	39
11	Second Order Basins of the Big Muddy and Saline River Basins	45

Chapter 1

INTRODUCTION

The Greater Egypt Regional Planning and Development Commission and the Southeastern Illinois Regional Planning and Development Commission have been involved in a study of water quality problems in their areas under a grant from the U.S. Environmental Protection Agency. The area of this study, to be called the Southern Illinois 208 area in this report, includes the counties Franklin, Gallatin, Hamilton, Hardin, Jackson, Jefferson, Perry, Pope, Saline, and Williamson (Fig. 1). The main emphasis of the study is on water quality problems related to coal mining.

This report, prepared in conjunction with the regional study, is a summary of the geological features of the coal mining portion of the ten-county area. The first part of the report is mainly a literature review of the physiography, structural geology, and stratigraphy of the area, with most of the emphasis on the coal-bearing rocks. The second part attempts to relate the geology to certain aspects of water quality, especially pH.

Figure 1. The Southern Illinois 208 project area. Counties are: 1. Perry, 2. Jackson, 3. Jefferson, 4. Franklin, 5. Williamson, 6. Hamilton, 7. Saline, 8. Pope, 9. Gallatin, 10. Hardin.

Chapter 2

PHYSIOGRAPHY AND TOPOGRAPHY

The Southern Illinois 208 area can be divided into several natural regions, each one being fairly uniform in bedrock, topography, and geologic history. Over half of the Southern Illinois 208 area, and nearly all of the coal-producing portion of the area, lies within the Mount Vernon Hill Country Natural Region (Fig. 2). The Mount Vernon Hill Country is an area of mature topography, with flat to gently rolling uplands and prairies, and broad alluvial valleys along the larger streams. Wooded hilly areas and low cliffs are present. The bedrock is dominantly shale accompanied by some thin, resistant sandstone layers, which tend to form ridges. A thin mantle of loess and Illinoian drift, which only slightly affect the topography, conforms to the bedrock surface. Glacial landforms are absent. The area is one of low relief, with the maximum difference between the highest and lowest elevations being on the order of 100 to 200 feet within a typical topographic quadrangle. The area has a completely developed drainage system characterized by streams that have broad terraced valleys and low gradients. Drainage is good in the uplands, but larger valley bottoms are poorly drained and are subject to frequent flooding (Leighton, et. al., 1948).

The next largest natural division of the Southern Illinois 208 area is the Shawnee Hills Division. This region is located south of the Mount Vernon Hill Country (Fig. 2) and extends across the state from Fountain Bluff on the Mississippi River eastward to the Shawneetown Hills. The topography is rugged, with a maximum relief on the order of 600 feet. The area is characterized by a high east-west escarpment of sandstone cliffs, the Greater Shawnee Hills, averaging 10 miles wide. To the south, a lower series of hills, the Lesser Shawnee Hills, average about 200 feet lower in elevation and contain some areas of karst topography. Because of the regional dip of the rocks, the north slopes of the hills, especially the Greater Shawnee Hills subdivision, are relatively gentle, but the south slopes are often quite steep (Illinois Nature Preserves Commission, 1973).

Along the eastern part of the area, especially in parts of Saline and Gallatin Counties, the landforms are a part of the Wabash Border Division.

LEGEND

A	Mount Vernon Hill Country Section of the Southern Till Plain Section
B	Wabash Border Division
C	Ozark Division
D	Lower Mississippi River Bottomlands Division
E	Shawnee Hills Division
F	Coastal Plain Division

Figure 2. Natural regions of Southern Illinois.

This includes the bottomlands of the Wabash River and its major tributaries as well as the loess-covered uplands adjacent to these areas. Most of this natural region was subject to Pleistocene glaciation, but in the Southern Illinois 208 area, glacial landforms are not present. The topography is gentle, with most of the relief consisting of low bluffs above the bottomlands. The rivers have very broad floodplains formed by glacial lakes; these floodplains tend to be poorly drained and marshy (Illinois Nature Preserves Commission, 1973).

A small area of Jackson County lies in the Lower Mississippi River Bottomlands Natural Region, which includes the Mississippi River and its floodplain. The bottomlands are broad and are built up of material deposited by glacial meltwater. Since the last episode of glaciation, the river has been meandering across this flat floodplain, leaving behind meander scars and oxbow lakes.

Another minor section of Jackson County lies in the Ozark Natural Region. Here the bedrock tends to be cherty limestone which is relatively resistant to erosion. This has given rise to a well-dissected plateau which rises above the Mississippi River floodplain. Steep slopes and bluffs border the floodplain, with ravines cutting into the plateau region from the floodplain.

The Coastal Plain Natural Region makes up a small part of Pope County. This is a region of swampy forested bottomlands and low clay and gravel hills (Illinois Nature Preserves Commission, 1973).

Chapter 3

STRUCTURE

The Southern Illinois 208 area is located near the south edge of the Illinois Basin, a major subdivision of the Eastern Interior Coal Basin (Fig. 3). The deepest part of the basin is located close to the point where Illinois, Indiana, and Kentucky join, but the geographic center is located northwest of this point. In general, rocks along the southern edge of the basin in Illinois tend to dip northward to northeastward toward the center of the basin. Typically the amount of dip is about one-half degree or less, or less than 45 feet per mile. This results in a sequency of stratigraphically higher and successively younger rocks going from south to north.

Several important structural features distrub this simple picture of Southern Illinois (Fig. 4). These include a large monocline, a syncline, and several fault zones. Two structural domes are also present, but will only be discussed briefly inasmuch as they do not greatly disturb the coal-bearing rocks.

Fairfield Basin

This is a subdivision of the Illinois Basin that includes the deepest part of the basin. Within the Southern Illinois 208 area, the Fairfield Basin occupies most of Jefferson, Franklin, and Hamilton Counties, about half of Saline and Gallatin Counties and northeastern Williamson County. It is bounded on the west by the east-facing DuQuoin Monocline, on the east by the LaSalle Anticlinal Belt and on the south by the Cottage Grove Fault System (Allgaier and Hopkins, 1975).

DuQuoin Monocline

The DuQuoin Monocline is located where the eastern edges of Jackson, Perry, and Washington counties adjoin the western edges of Jefferson and Franklin counties. This east-facing, north-south trending structure drops rocks downward over two hundred feet on the eastern side.

Preceding page blank

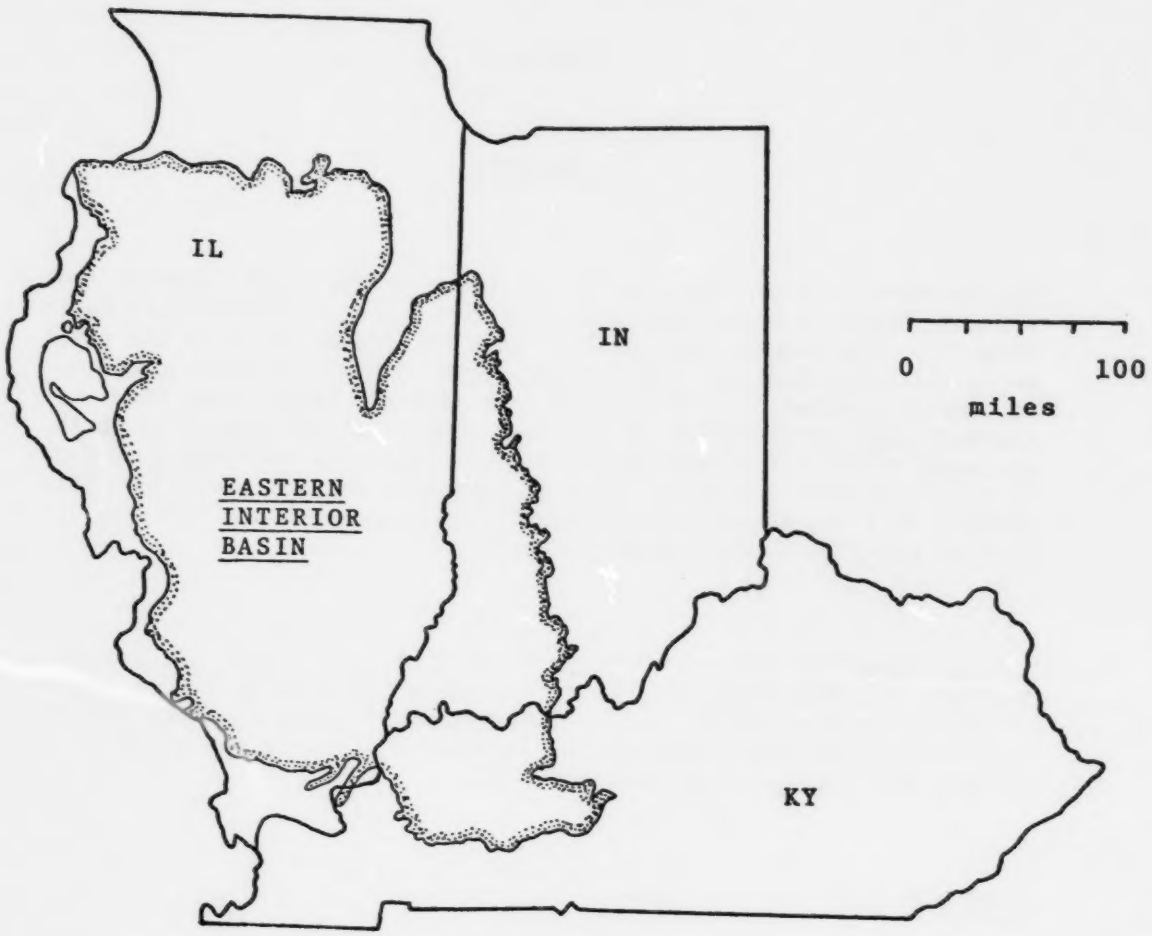

Figure 3. The Eastern Interior Basin in Illinois, Indiana and Kentucky.

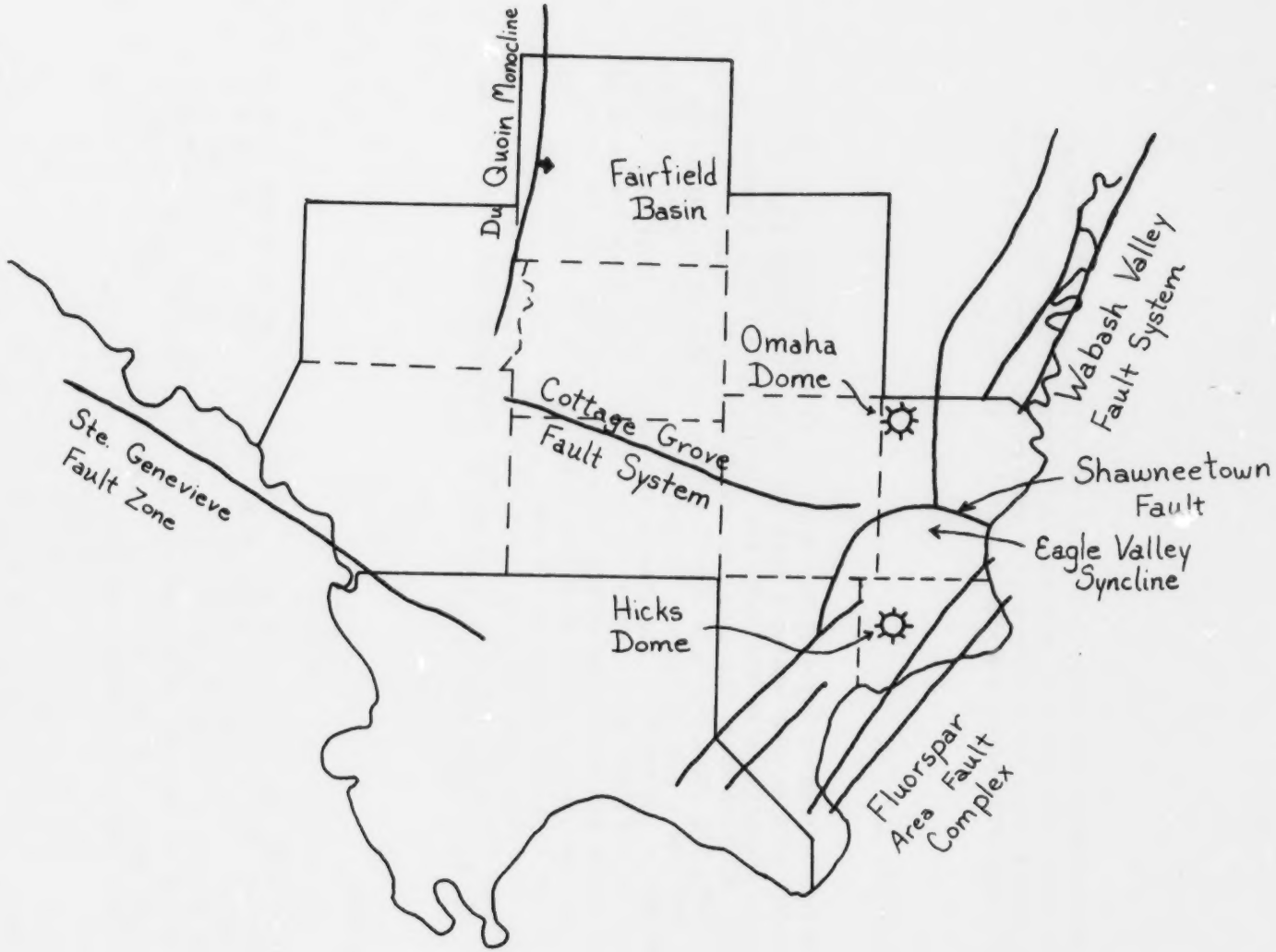

Figure 4. Major structural features of the Southern Illinois 208 area (Modified from Willman, et. al., 1975).

The DuQuoin Monocline strongly affects the thickness of the Pennsylvanian rocks that cross it, and thus was active during Pennsylvanian time, separating a relatively stable western shelf area from a more rapidly subsiding basin (Fairfield basin) to the east.

Eagle Valley Syncline

The westward-trending Eagle Valley Syncline is located mainly in Gallatin County but also extends westward into Saline and southward into Hardin Counties. Pennsylvanian age rocks are stongly folded into a narrow syncline which reverses the usual northward dip of the rocks. On the south limb, the rocks dip less than 5 degrees to the north, and on the north limb the dip is as much as 25 degrees to the south. The syncline is bounded on the north by the Shawneetown-Rough Creek Fault Zone. The syncline is outlined by resistant ridges of lower Pennsylvanian sandstone of Caseyville and Abbott Formations. The center of the suncline is a series of low hills of Anvil Rock Sandstone (Carbondale Formation). The axis of the syncline plunges to the east, and the syncline becomes deepest and widest near the Ohio River before dying out in Kentucky. On the western side, the syncline bends to the southwest, and then dies out (Cote, et. al., 1969; Wilson, 1959).

Omaha Dome

The Omaha Dome is a relatively small, roughly circular structure located in northwest Gallatin County (English and Grogan, 1948). It raises the rocks within it well above the position they have in the nearby basin. The No. 6 coal is raised by as much as 300 feet and comes to within 100 feet of the surface (Allgaier and Hopkins, 1975). Extensive drilling for oil in the area, with laws governing mining adjacent to oil wells, make it unlikely that this shallow area of coal could be mined.

Hicks Dome

This uplift is located in western Hardin County and dominates the structure in the area. It is an asymmetric feature elongated toward the southeast. The structural center has 4000 feet of vertical uplift and brings Devonian age rocks to the surface. Rocks dip away from this center in all directions, with the steepest dips toward the north and northwest into the Eagle Valley Syncline. Hicks Dome is the structurally

highest part of a large southeastward trending anti-cline that extends into Kentucky. This large fold has been obscured by collapse along a very complex system of faults (Baxter, Desborough, and Shaw, 1967). Except along the flanks, Pennsylvanian age rocks that might have been present on the dome have been removed by erosion.

Shawneetown Fault Zone

This is a high angle reverse fault along which the strata have been displaced as much as 3500 feet, with the rocks on the south moved upward with respect to those on the north. The structure enters Illinois from Kentucky in souther Gallatin County and curves around to the southwest in southeastern Saline and northeast Pope County, where it merges with the Fluorspar District Fault System. The Shawneetown Fault, which occurs on the north edge of the Eagle Valley Syncline, separates sediments that dip gently toward the center of the Illinois Basin in a normal fashion from the strongly folded rocks of the Eagle Valley Syncline (Wilson, 1959; Cote, et. al, 1969).

Cottage Grove Fault System

This feature is an east-southeast oriented group of faults that crosses middle Saline, northeast Williamson, and southwest Franklin Counties. It begins not far from the Shawneetown Fault and terminates close to the south end of the DuQuoin Monocline. This system is sometimes used to mark the south boundary of the Fairfield Basin. In Saline County, the Cottage Grove Fault System is upthrown on the north side along most of its trend. Displacement varies considerably, but is usually less than 50 feet (Hopkins, 1968). In Williamson County, the fault zone is for the most part a narrow horst (an upthrown block between two downthrown blocks). The northern most fault is downthrown to the north-northeast and the southernmost fault is downthrown to the south-southwest. In this county the faults also have variable displacement, but again it its usually less than 50 feet (Hopkins, 1968).

Wabash Valley Fault System

This is a series of high angle faults trending south to southwest near and approximately parallel to the Wabash River. The downthrown side is on the east, and displacements are on the order of 100 to 300 feet. These faults break the coal-bearing rocks into relatively large blocks in northern Gallatin County and change the dip from north to northwesterly in central and eastern Gallatin County. Faults of this same

trend are located southwest of the study area in southernmost Illinois, Kentucky, Tennessee, and Missouri, where the zone is called the New Madrid Fault Zone.

Fluorspar Area Fault Complex

While not the focus of this report, no discussion of structure would be complete without mentioning the Fluorspar Area Fault Complex. Pope and Hardin Counties are the area of convergence of several complex structural features. The Wabash Valley and New Madrid Fault Systems converge here, and the Shawneetown Fault cuts across the northern end of the area, marking the north end of the folding that formed Hicks Dome and the Eagle Valley Syncline. The projection of the Sainte Genevieve Fault Zone from the western part of the state also would intersect this area. Faulting in the area is very complex, and many of the faults have served to localize fluorspar ore deposits. The main effect of the faulting with respect to coal deposits is that the faulting has structurally dropped several fairly large blocks of Pennsylvanian rocks and has allowed them to be preserved from erosion.

Chapter 4

STRATIGRAPHY

The coal-bearing rocks of Illinois are Pennsylvanian in age, with most of the coal occurring in rocks of Middle Pennsylvanian age. Total thickness of the Pennsylvanian section in Southern Illinois ranges from about 1500 feet in Perry, Randolph, and Jackson Counties to about 2500 feet in Gallatin, Williamson, and Saline Counties. Several formations with many subdivisions (members) are presently recognized, and cyclic sedimentation patterns are present within each of the formations. Pennsylvanian formation of interest in this report are, from oldest to youngest, Caseyville, Abbott, Spoon, Carbondale, Modesto, Bond, and Mattoon. One other formation, the Pleistocene age Equality other formations are present in the Southern Illinois 208 area, they are mostly older than the coal-bearing units and, in keeping with the objectives of the report, will not be discussed.

During late Mississippian time, the present Illinois Basin was covered by a shallow sea that lay mainly to the south of the area. The sea withdrew near the end of Mississippian time and the land surface was subjected to erosion. A series of northeast-southwest oriented valleys developed over the eastern part of the area. In early Pennsylvanian time, the Illinois Basin once again sank and was gradually invaded by a shallow portion of the large sea that occupied the area to the south. A delta complex developed, and depositional environments changed rapidly in response to subsidence and building out of the delta. The area occupied by the delta slowly subsided and kept receiving sediments even as nearby areas were still undergoing erosion. The DuQuoin Monocline marked the approximate western edge of the main area of subsidence and deltaic deposition. The deposition of the Colchester (No. 2) Coal Member of the Carbondale Formation marks the point when the entire area had sunk enough to be covered by Pennsylvanian age sediments (Bristol and Howard, 1971). Sedimentation continued into upper Pennsylvanian time, with the area west of the DuQuoin Monocline continuing to be mainly dominated by clastic deltaic sediments whereas the western shelf had a greater marine influence and is characterized by the higher percentage of carbonate rocks.

There are no strata between Pennsylvanian and Cretaceous age in Illinois so the geologic history of that interval of time cannot be fully deciphered. Some igneous rocks of Permian age are present, but the next episode of sedimentation of which there remains any record is the Cretaceous deposits of extreme Southern Illinois. A minor amount of this material is present in the Southern Illinois 208 area.

Caseyville Formation

In the western part of Southern Illinois, i.e., St. Clair, Randolph, western Perry, and western Jackson Counties, Caseyville rocks are either thin or absent. However, east of the DuQuoin Monocline (i.e., eastern Perry and Jackson Counties and further east), Caseyville rocks reach thicknesses of 300 to 400 feet and may occasionally reach over 500 feet. This variation in thickness of the formation is due to both the irregular subsidence of the areas east and west of the DuQuoin Monocline as well as the irregular surface upon which the formation was deposited (Smith, 1958; Kosanke, et al., 1960; William, et al., 1975).

The Caseyville Formation (Fig. 5) is dominated by clean, well-sorted quartz sandstone characterized by the presence of small white quartz pebbles. The sandstones, which make up more than 60 percent of the formation, are frequently channel-form and may attain thicknesses of over 100 feet. Cross-bedding is common in the channel facies. The sandstones, especially the thick channel facies, are resistant to erosion and form the prominent hills and cliffs of the Pennsylvanian escarpment in Southern Illinois. The remaining portion of the formation consists of siltstone and silty or sandy shale. Limestones are virtually absent, and the rare coals are thin, lenticular, and discontinuous (Willman, et al., 1975). Coals have been mined from this formation in the past in southeastern-most Jackson County near Makanda (Smith, 1958; Lamar, 1925).

The Caseyville Formation has recently been extensively studied by Ethridge and co-workers. The reader is referred to the many papers contained in two guidebooks by Ethridge and Fraunfelter (1976) and Ethridge, Fraunfelter, and Utgaard (1973) for detailed discussions. In general, these investigators think the Caseyville Formation represents a shallow water delta which rapidly prograded across a slowly subsiding continental shelf area. The depth of the water body in which the delta was forming is estimated to have been from about 40 to 80 feet (Ethridge and Bailey, 1976). Prodelta muds, distributary bars, distributary channels, delta plains, interdistributary bays, delta destructional facies, and crevasse splay deposits, all characteristic of deltaic environments, have been recognized in Caseyville Formation rocks.

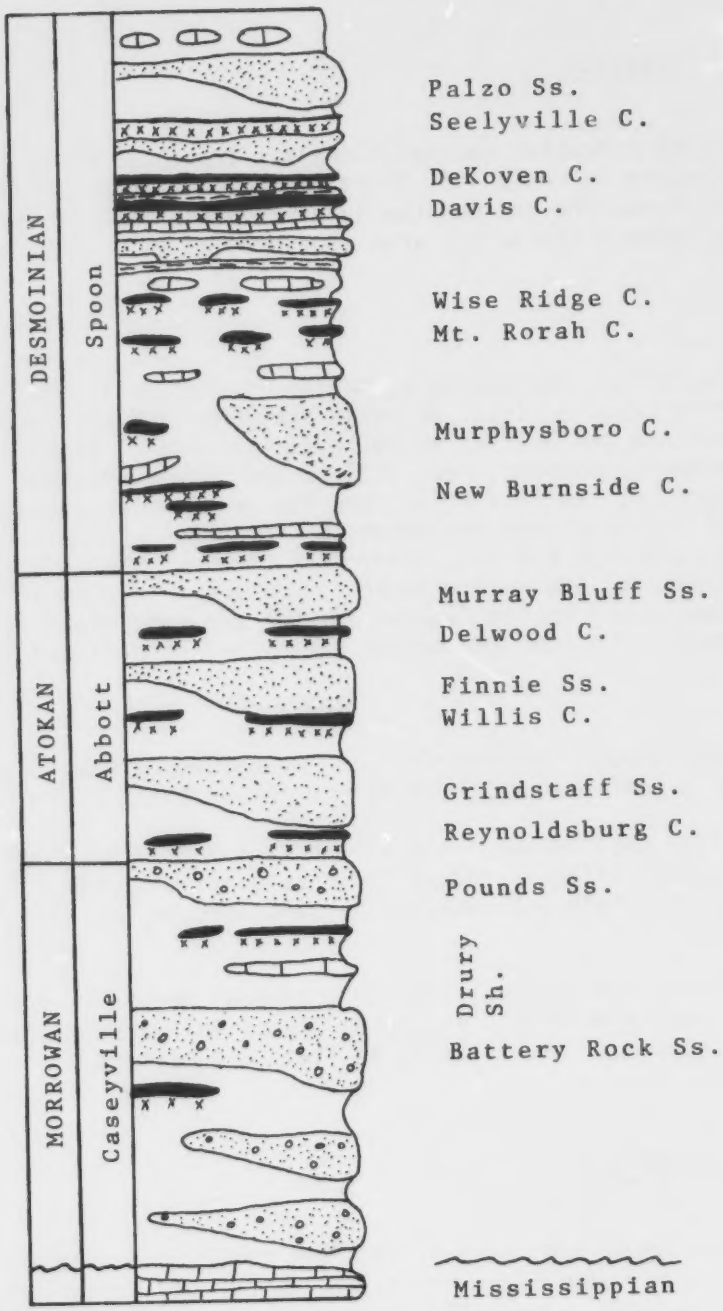

Figure 5. Stratigraphic column of the Caseyville, Abbott and Spoon Formations (adapted from Willman, et al., 1975).

Abbott Formation

The Abbott Formation reaches a maximum thickness of about 350 feet in southeastern Illinois. It thins westward to about 50 feet west of the DuQuoin Monocline and eventually nearly thins out in the western part of the Southern Illinois 208 area (Kosanke, et al., 1960; Willman, et al., 1975).

Lithologically, the Abbott Formation is similar to the Caseyville Formation below it (Fig. 5), with about half of the formation consisting of sandstone and half of shale (Kosanke, et al., 1960). The sandstones are generally thinner, less well sorted, finer grained, and more micaceous than those of the Caseyville, and the small white pebbles that characterize Caseyville sandstones are absent in the Abbott Formation. Shales of the Abbott Formation are less sandy than those of the underlying Caseyville, and limestones are nearly absent. Coals are thicker and a little more persistent than in the Caseyville, but are not generally of economic importance. Some of the better known coals are listed below.

a. Reynoldsburg Coal Member. The Reynoldsburg Coal Member is present mainly in Johnson County and not in the Southern Illinois 208 area.

b. Willis Coal Member. The Willis Coal Member has been mined in southeastern Illinois, where it occasionally reaches 3.5 feet thick. It is both underlain and overlain by sandstone in the type area in Gallatin County.

c. Delwood Coal Member. The Delwood Coal Member is present in Pope County and other widely scattered places in Southern Illinois. In places this coal may reach three feet in thickness.

Spoon Formation

The Spoon Formation is about 350 feet thick in southeastern Illinois and, like the underlying Abbott and Caseyville Formations, it thins toward the west, especially after crossing the DuQuoin Monocline, westward of which thicknesses are on the order of 100 feet (Kosanke, et al., 1960).

The lithology of the Spoon Formation is somewhat different than the underlying Abbott and Caseyville Formations (Fig. 5). The shales

contain less sand and silt than those of the underlying formations. Black shales and underclays below coal beds are more common than in the lower formations. Sandstones of the formation are not markedly different from those of the Abbott, although they tend to be more argillaceous and micaceous. Both channel and sheet facies of sandstones are present. Limestones are thin but have appreciable lateral extent. They make up only a small amount (1 to 2 percent) of the formation.

Coals of the Spoon Formation are the earliest widespread coals of Pennsylvanian age in Southern Illinois. Coals of economic importance, as described in Willman, et al. (1975), are listed below.

a. New Burnside Coal Member. This coal is well developed but outcrops are scattered. It attains thicknesses up to 5 feet.

b. Murphysboro Coal Member. Occurring in Jackson and western Williamson Counties, this coal locally attains a thickness of 7 feet and is presently being mined clos[illegible]he Jackson-Williamson county line. It is not uniformly well deve[illegible] over the area of its occurrence.

c. DeLong Coal Member. Seldom over two feet thick, this coal occurs sporadically throughout Southern Illinois.

d. Wise Ridge Coal Member. This is a thin, lenticular coal widely distributed across Southern Illinois. It is too thin to be of economic importance.

e. Davis Coal Member. The Davis is an important commercial coal in Southern Illinois. It averages about four feet thick in much of the eastern part of Southern Illinois where it has been extensively mined.

f. DeKoven Coal Member. This coal occurs from a few feet to 40 feet above the Davis coal and the two are commonly mined together. The DeKoven coal averages three feet in thickness, and it occurs mainly in southeastern Illinois.

The stratigraphic interval between the Davis and DeKoven coals merits special mention. This zone frequently contains a black shale that is very pyritic. Where the pyritic share is exposed to weathering, it produces some of the worst acid mine drainage problems in Southern Illinois.

The combined thicknesses of the Caseyville, Abbott, and Spoon formations reflect and amplify the westward thinning trend discussed under each individual formation. This portion of the Pennsylvanian has a maximum thickness exceeding 1200 feet in eastern Williamson and western Saline Counties, thins westward to slightly over 200 feet in northwestern Perry County, and becomes even thinner northwest from there. The greatest change in thickness occurs in the vicinity of the DuQuoin Monocline.

Carbondale Formation

The Carbondale Formation (Fig. 6) is presently defined as the interval from the base of the Colchester (No. 2) Coal Member to the top of the Danville (No. 7) Coal Member (Kosanke, et al., 1960). The thickness of the Carbondale Formation follows the same general trend as the other Pennsylvanian formations. At the northern edge of its outcrop area in Saline County, it reaches over 400 feet in thickness, and thins gradually both eastward and westward. Across the DuQuoin Monocline it thins rapidly to about 225 feet and continues the thinning trend westward until it reaches a thickness of about 175 feet along the Perry County-Randolph County border (Smith, 1958; Kosanke, et al., 1960).

The Carbondale Formation consists mainly of gray shale and gray silty shale, which make up about 65 percent of the formation. Sandstones are locally prominent and, when in channel form, may reach thicknesses of 100 feet. Sheet-form sandstones are much thinner. The sandstones of the Carbondale Formation are commonly subgraywackes and tend to be more argillaceous than the older Pennsylvanian sandstones (Willman, et al., 1975). Sandstones make up about 25 percent of the formation (Kosanke, et al., 1960).

Limestones are fairly common, widespread and persistent. A typical limestone is gray to dark gray, argillaceous, and contains marine fossils. The typical thickness of the limestones is one to five feet, but they occur frequently enough to make up about 5 percent of the formation.

Coals make up roughly 5 percent of the Carbondale Formation (Kosanke, et al., 1960). They are abundant, widespread, and persistent. Many are relatively thick, commonly ranging from 2 to 7 feet and occasionally reaching 15 feet in thickness. Below is a list of the coals of the formation, in ascending stratigraphic order, beginning with the

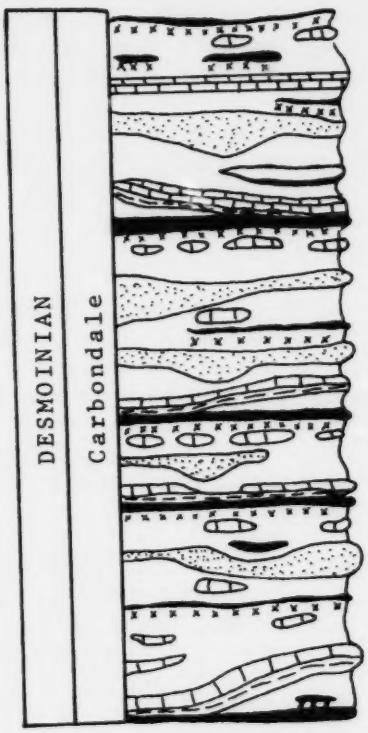

Figure 6. Stratigraphic column of the Carbondale Formation (adapted from Willman, et. al., 1975).

Colchester (No. 2) Coal Member at the base of the formation (Willman, et al., 1975).

a. Colchester (No. 2) Coal Member. This is a very persistent coal that locally reaches a maximum thickness of 18 inches in Southern Illinois. Although it does not appear to reach minable thickness in the area, its persistence makes it useful as a stratigraphic indicator horizon.

b. Shawneetown Coal Member. This was formerly called the No. 2A Coal in southeastern Illinois. It is normally quite thin but in a few scattered drill holes has been reported to reach 8 feet. Where found, it is generally about 50 feet above the No. 2 coal. It tends not to be present in the western part of the area.

c. Summum (No. 4) Coal Member. This is another widespread, persistent coal used as a stratigraphic marker. Generally thin, the coal is reported to reach a maximum thickness of 2 to 3 feet in scattered drill holes in Randolph, Perry, and Jackson Counties. It has been mined in a few places in southeastern Williamson County and in Saline County. It is associated with a black fissile shale horizon, 6 to 8 feet thick, that overlies the coal and makes the stratigraphic interval of the coal evident even when the coal is missing.

d. Harrisburg (No. 5) Coal Member. This is the second-most commercially important coal in Illinois. It overlies the No. 4 by an interval of 50 to 80 feet with the lower end of this range being more common in southwestern Illinois. Thickness of the coal reaches over 7 feet in Saline and Gallatin Counties. It thins westward to less than 30 inches in most of the area west of the DuQuoin Monocline. One known exception to the low thickness west of the monocline is in the southwestern corner of Perry County and in an adjacent area in Randolph County, where the coal is from 5 to 7 feet thick.

e. Briar Hill (No. 5A) Coal Member. This is a thin, discontinuous coal of little commercial importance. It seems to occur only in Gallatin and Saline Counties within a zone of sandy strata. It reaches 18 to 30 inches in the Eagle Valley Syncline, but its thickness is very erratic.

f. Herrin (No. 6) Coal Member. This is a bright-banded coal which ranks first in commercial importance in the state. The thickness pattern of the No. 6 coal is unlike that of most of the Pennsylvanian units in Southern Illinois. The No. 6 coal tends to thicken going from eastern Gallatin County, where it tends to be less than 4 feet thick, toward western Williamson and northeastern Jackson County, where

it attains a thickness of 8 to 9 feet. However, right in the middle of this zone of thick coal, there is a coal cut-out; this is caused by a sandstone channel located approximately along the border of Williamson County with Perry and Jackson Counties. West of the cut-out, the coal thins to the five to seven feet range.

g. Jamestown Coal Member. This is a thin coal, seldom more than a few inches thick. Four to six inches is the usual thickness in the eastern counties.

h. Danville (No. 7) Coal Member. This coal was formerly known in southeast Illinois as the Cutler Coal. It reaches a maximum thickness of about 18 inches in southwestern Illinois and up to a maximum of 30 inches in the southeastern counties.

The interval between the No. 5 and No. 6 coals is of considerable significance because this material is the overburden rock that makes up the mine spoil in strip mining of the No. 5 coal. The thickness of this interval ranges from about 125 feet in eastern Saline County to slightly less than 50 feet in western Williamson County (Smith, 1957). It continues to thin westward, going from a typical thickness of 35 feet in Jackson County down to about 25 feet in western Perry County and in the adjacent parts of Randolph County (Smith, 1958).

The nature of the strata within this interval also varies across Southern Illinois. In general, a black shale containing ironstone or limey concretions overlies the No. 5 coal. This shale is on the order of 1 to 3 feet thick (Smith, 1958; Willman, et al., 1975). Overlying the black shale is the St. David Limestone Member. This is a rather thin brownish gray limestone, varying in thickness from a few inches to a few feet. In the western part of the Southern Illinois 208 area, thickness may reach 3 or 4 feet but it thins eastward. In southeastern Williamson County, it is about a foot thick and continues to thin to a few inches further east (Hopkins, 1968; Willman, et al., 1975).

In places, the Dykersburg Shale Member intervenes between the No. 5 Coal Member and the black shale that occurs below the St. David Limestone Member. This rock unit is found in a belt from three to fifteen miles wide that extends southwest from Wabash County to the outcrop area in eastern Williamson and western Saline Counties, at which point it is nearly 30 miles wide (Hopkins, 1968). The Dykersburg Shale Member is a gray, silty shale which contains some sandstone layers. A long channel sandstone, from one-half to three-quarters of a mile wide, extends along the eastern part of the shale area and cuts out the No. 5 coal. This channel may reach a thickness of 40 feet.

The Canton Shale Member overlies the St. David Limestone Member. This is a gray, farily uniform shale that commonly contains calcareous concretions (Willman, et al., 1975). It varies in thickness from about a foot in parts of Perry County to perhaps fifty feet in Williamson County. Where the interval between the No. 5 and No. 6 coals is thin, the Canton Shale may also grade upward into the No. 6 coal underclay, which commonly is on the order of 5 to 8 feet thick (Smith, 1957, 1958).

In Saline and Gallatin Counties, an intermediate coal, the Briar Hill Coal Member (No. 5A), appears within the Canton Shale Member about 60 feet above the No. 5 and 40 to 60 feet below the No. 6 coal. When the Briar Hill Coal Member is present, it is frequently overlain by a black shale one to two feet thick (Cady, et al., 1951). Also present in the Saline and Gallatin County area are sandy strata up to 20 feet thick which lie at the top of the Canton Shale and below the No. 6 Coal Member underclay (Smith, 1958; Cady, et al. 1951). These sandy strata, as well as a sandstone that sometimes underlies the Briar Hill Coal Member, may be equivalent to the Vermillionville Sandstone Member known elsewhere in the state (Hopkins, 1968; Willman, et al., 1975).

Because they are so frequently the overburden material of strip mines in the Southern Illinois 208 area, the strata above the No. 6 Coal Member merit more detailed discussion.

Typically, the No. 6 Coal Member is overlain by a black shale of sheety fissility, the Anna Shale Member. This shale ranges from one to four feet in thickness, with a usual thickness of less than two feet (Allgaier and Hopkins, 1975; Willman, et al., 1975).

Fossil assemblages at the very bottom suggest brackish water, but it contains marine fossils at higher levels (Granda, 1969). Three things about this shale are striking: (1) the absence of a bottom-dwelling fauna although other fauna are present; (2) the almost complete absence of disturbance of the laminae of the shale; and (3) a carbon content high enough so that the shale will sometimes burn. Another important feature is the presence of abundant pyrite. These characteristics have led investigators to interpret this shale as representing the first marine transgression over the peat swamps in which the No. 6 coal accumulated. The water is thought to have been shallow, with the bottom stagnant and poisoned with hydrogen sulfide from decaying organic matter. The fine, undisturbed laminae suggest the bottom was protected from waves, tides, and storms; it has been suggested that a thick algae

mat could have provided the protection as well as the organic debris of the shale (Grenda, 1969; Givens, 1967; Utgaard and Givens, 1973).

Intervening in places between the Anna Shale Member and the No. 6 Coal Member is the Energy Shale Member. This is a gray shale that is similar in lithology and occurrence to the Dykersburg Shale above the No. 5 coal. This shale occurs in a roughly north-south band up to 20 miles wide, extending from southwestern Jefferson County southward into Franklin, Williamson, and Jackson Counties. The Energy Shale may attain a thickness of as much as 100 feet, and where it is present the Anna Shale Member and the overlying Brereton Limestone Member become thin and may not be present. When the shale is greater than 20 feet thick, it tends to grade upward into a silty shale which in turn grades upward or laterally into sandstone. The sandstone occupies a channel (the Washville Channel) that may be as much as 50 feet thick and up to 2 miles wide. This channel can be traced southward from Christian County to Franklin and Jackson Counties, a distance of more than 100 miles, and cuts out the No. 6 coal over much of this length (Allgaier and Hopkins, 1975).

The Brereton Limestone Member overlies the Anna Shale, although in places the Anna Shale is missing and the Brereton Limestone is directly on the No. 6 coal (Smith, 1958; Allgaier and Hopkins, 1975). The Brereton Limestone Member is a normal marine fossiliferous limestone that can become quite argillaceous in places. Typically the Brereton Limestone is about 4 feet thick, but it may thicken to 10 feet and thin to much less than a foot (Allgaier and Hopkins, 1975).

Sediments of the Jamestown Cyclothem appear just above the Brereton Limestone in parts of southeastern Illinois. The first unit of this cyclothem in an unnamed gray shale. It contains marine fossils similar to those of the Brereton Limestone at the top and bottom, but it is only sparsely fossiliferous in the middle, probably due to rapid accumulation of mud. It is interpreted as a prograding delta front.

Above the unnamed gray shale is a marine limestone only a few inches thick. It is very similar to the Brereton Limestone, except that it contains fossil roots and served as a base upon which grew the plants that formed the next unit above, the Jamestown Coal. This coal is usually only a few inches thick. Its presence on the limestone may indicate a slight shoaling of the water or perhaps a replacement of the marine water with fresh water. Above the Jamestown Coal, another

thin limestone, the Conant Limestone Member, is present. It is very similar to the limestone below the coal.

Overall, the sequence from the unnamed gray shale just above the Brereton Limestone through the Conant Limestone comprises the Jamestown Cyclothem. This entire sequence is lacking in the northwestern part of the Southern Illinois 208 area, and it appears to be a clastic wedge that entered Southern Illinois from the east and interfingered with marine sediments in the Williamson and Saline Counties area. In other places in southern Illinois, the Lawson Shale Member lies directly on the Brereton Limestone (Givens, 1967).

The next unit upwards is the Lawson Shale Member, which lies either on the Brereton Limestone or on the sediments of the Jamestown Cyclothem, depending on location. This is a medium gray, silty, carbonaceous shale that appears to have been either a delta front mud (Wetendorf, 1967) or an interdistributary bay deposit (Utgaaard and Givens, 1973).

Above the Lawson Shale Member is the Anvil Rock Sandstone Member, a light gray, very fine- to medium-grained, micaceous, argillaceous sandstone. Both sheet and channel phases are common. The channel phase becomes thick enough (80 feet) that it has eroded out the No. 6 Coal in several places in southern Illinois. The name "Anvil Rock" was also applied in the past to rocks that are now referred to as the "Washville Channel" (Willman, et al., 1975; Allgaier and Hopkins, 1975).

The Bankston Fork Limestone Member, an argillaceous fossiliferous marine limestone, overlies the Anvil Rock Sandstone Member, although it is usually separated from it by a few feet of shale. It is usually not more than six feet thick, and frequently contains a layer of shale that divides it into two benches.

A thin coaly zone is present one or two feet above the Bankston Fork Limestone Member in parts of Williamson, Saline, and Gallatin Counties. This is the Allenby Coal Member, which is not of commercial importance in Illinois. Greenish gray to gray shale occurs above the coal, and an underclay is between it and the Bankston Fork Limestone Member (Willman, et al., 1975).

The Galum Limestone Member is a part of the Carbondale Formation that is found in Perry County and nearby areas. It is unpure and thin, seldom more than three feet in thickness. A few feet of gray shale, which may be equivalent to the gray shale above the Allenby Coal Member further east, lies between the Galum Limestone and the Bankson Fork Limestone below it. The material above the Galum Limestone Member is the underclay of the Danville (No. 7) Coal.

The uppermost member of the Carbondale Formation is the Danville (No. 7) Coal Member, which was (and to some extent still is) called the Cutler Coal in parts of the Southern Illinois 208 area. It is too thin to be of economic importance in the area, but it does show up in the highwall of some strip mines (for example, Captain Mine).

Modesto Formation

The Modesto Formation is the youngest Pennsylvanian formation found in most of the coal-producing area of southern Illinois. In most of Perry County the thickness of the Modesto Formation is 225 feet. East of the DuQuoin Monocline, the thickness increases to over 375 feet in northeast Williamson County, and thins again to a little over 300 feet thick in northernmost Saline and Gallatin Counties. North of the outcrop area of this formation, the thickness reaches 450 feet near the northeast corner of Franklin County (Willman, et al., 1975).

The Modesto Formation is characterized by gray shale, but sandstones are locally prominent. The approximate distribution of lithologies, according to Kosande, et al. (1960), is about 70 percent shale, 25 percent sandstone, 5 percent limestones and less than 1 percent coal (Fig. 7). It has thicker limestones and thinner coals than the underlying Carbondale Formation, and the presence of red shales also serves to distinguish it from the older formation. Coals in this formation are less than a foot thick and are not usually of commercial importance.

Only two members of this formation merit mention here. The Farmington Shale Member is the lowest member of the formation. It is a gray shale with marine fossils in the lower part. It generally lies directly on the Danville Coal Member, but in places thin impure limestone or black shale may occur between the two. Thickness is variable, with a maximum of 100 feet or more reported in southeastern Illinois. The Piasa Limestone Member (formerly called the Cutler Limestone) lies a few feet above the No. 7 coal. It is generally less than 4 feet thick in the

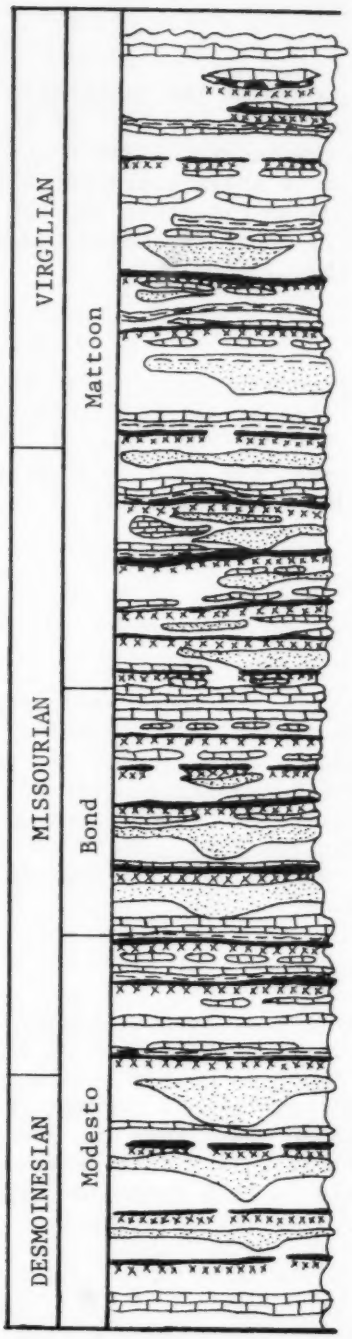

Figure 7. Stratigraphic column of the Modesto, Bond and Spoon Formations (adapted from Willman, et. al., 1975).

southwestern part of the region but thicken to about 15 feet toward the east, where it is known as the West Franklin Limestone. This is a persistent limestone horizon, which because of its stratigraphic position in the lower part of the Modesto Formation, may occasionally be encountered in strip mine overburden in areas where the Carbondale Formation is thin (i.e., west of the DuQuoin Monocline).

Bond Formation

The Bond Formation is exposed mainly in Jefferson, Franklin, and Hamilton Counties in the Southern Illinois 208 area. In this region it varies from about 175 to 250 feet thick (Willman, et al., 1975). It is characterized by a relatively high percentage of limestone. Both the upper and lower boundaries of the formation are thick, pure limestones. The bulk of the formation is gray shale, much of which is calcareous (Kosanke, et al., 1960; Willman, et al., 1975). Siltstones, sandstones, and occasional red shales are also present. The coals of the formation are typically less than one foot thick and are not of commercial importance (Willman, et al., 1975).

Mattoon Formation

The outcrop area of this formation is in northeastern Jefferson and northern Hamilton Counties. Total thickness of this formation in the area is slightly over 200 feet, but only the lower part of the formation is present. It is the youngest Pennsylvanian formation in the state.

The lithology of the Mattoon Formation is a mixture of thin limestones, coals, fissle black shale, a lot of gray shale and quite a bit of sandstone, much of which is calcareous (Willman, et al., 1975; Kosanke, et al., 1960). In the Southern Illinois 208 area, the coals of this formation are very thin and of no commercial importance, with one exception. The exception is the Opdyke Coal Member, which is named after the village of Opdyke in Jefferson County. Near this location the coal attains a thickness of two feet and is mined. The overburden above the coal is a soft, medium calcareous gray shale about 10 feet thick that contains some marine fossils. The material above the shale is Pleistocene glacial till, about 6 feet thick.

Equality Formation

The presence of broad, poorly drained floodplains in the Mount Vernon Hill Country and Wabash Border Natural Regions has been mentioned previously. These floodplains and surrounding areas are the location of the Equality Formation, a group of unconsolidated lake sediments ranging from sand to silt and clays. The formation was named by Willman and Frye (1970) for exposures along the Saline River near Equality in Gallatin County, where the sediments are well exposed.

In southern Illinois, a relatively mature topography had developed prior to the advance of the Illinoian Glacier. This glacial episode was marked by an advance of the ice as far south as the Shawnee Hills area. The area north of the Shawnee Hills was mantled by a thin layer of drift, some of which still remains. Subsequent to this, an interval of erosion weathered and removed some of the glacial debris and a drainage pattern similar to the present one became established in the area. Beginning about 21,000 years ago, as the last major ice sheet began to recede, silt-laden meltwater flooded the Mississippi, Ohio, and Wabash valleys, filling these main valleys with sediment and causing the development of slackwater lakes in river valleys adjacent to these main drainageways. Development of such lakes was extensive in southern Illinois and included large portions of the Big Muddy, Saline, and Skillet river valleys (Fig. 8), which were occupied by Lake Muddy, Lake Saline, and Lake Skillet, respectively (Frye, et al., 1972). A brief summary of Lake Saline is presented below; presumably the history of the other lakes is very similar.

Prior to the establishment of Lake Saline, streams were incised into the bedrock and Illinoian till to a depth of 100 to 150 feet below the level of the present rivers. When meltwater of the earliest phase (Altonian) of the most recent glacial stage occurred, sediment-laden water alluviated the master streams to such an extent that the tributary valleys, of which the Saline was one, became blocked off and filled with water. The tributary valleys were then partly filled with sediment, some of which was brought in by erosion of the adjacent land areas and some of which was contributed by the major streams.

This first episode of filling was followed by a period of erosion, only to be repeated as Woodfordian outwash once again filled the master valleys and re-established the slackwater lakes. During this episode, about 21,000 years (radiocarbon) before the present, the shorelines of Lake Saline were at an elevation of about 360 feet. The lake eventually rose to a level of 400 feet. During this period, sufficient

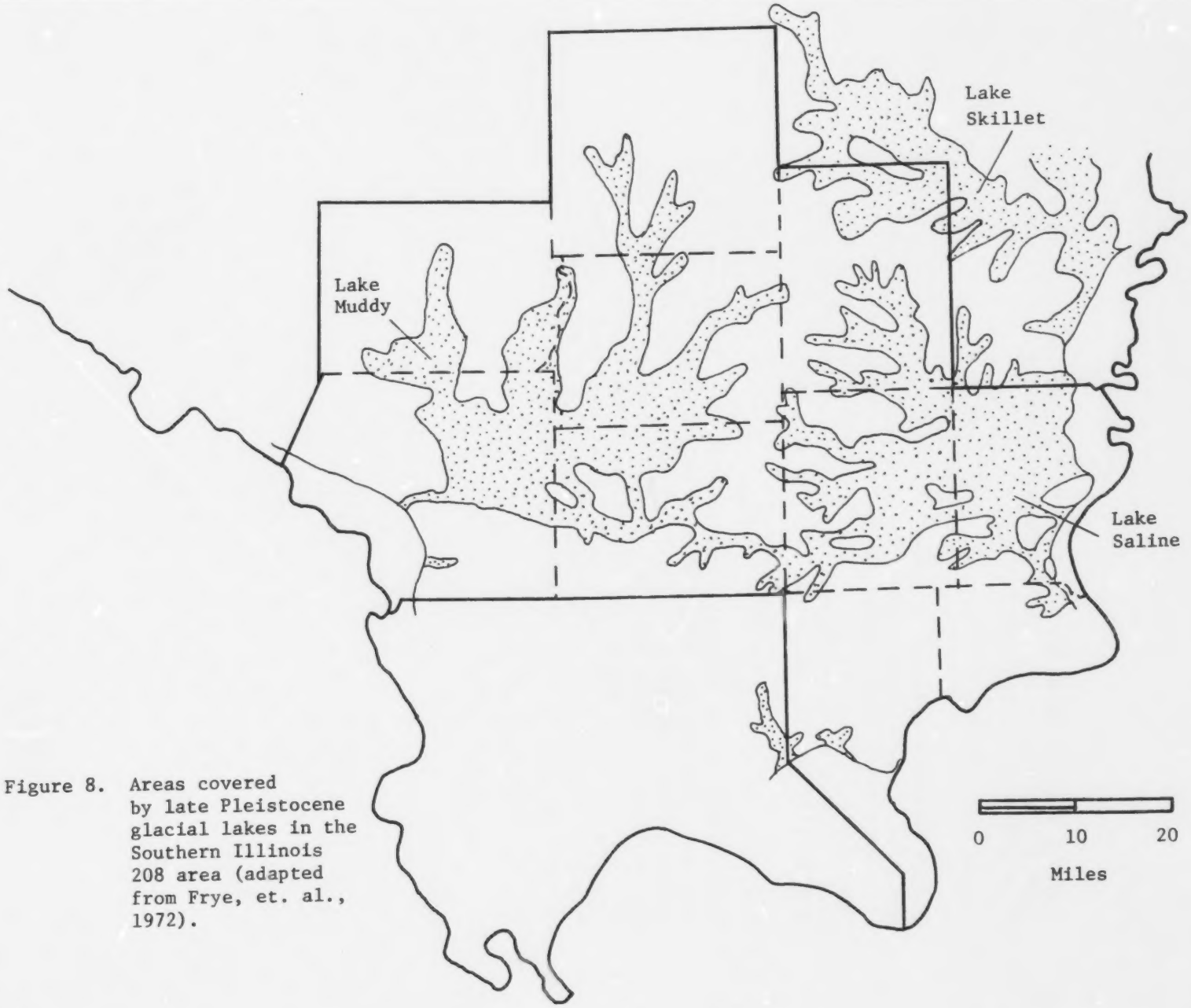

Figure 8. Areas covered by late Pleistocene glacial lakes in the Southern Illinois 208 area (adapted from Frye, et. al., 1972).

sediment accumulated on the floor of the lake to effectively bury the pre-existing topography. These sediments presently form a broad plain at an elevation of about 380 feet.

Another period of erosion, followed by a third period of lake sedimentation, ensued. This stage is marked by terraces of sediment having elevations of about 350 to 360 feet. The history of the lake ended about 13,000 years ago. Since that time, the major streams have been eroding their floodplains and the tributary streams have been eroding the lake sediments (Frye, et al., 1972).

The sediments of the Equality Formation are important in terms of land use. They are not likely to contribute acid to mine drainage waters and the presence of calcareous nodules in some indicate they may have neutralization potential. They do, however, present a problem in terms of surface mining activities. These materials are unconsolidates, clay rich, and are often water-saturated. They have little bearing strength and will present serious problems whenever attempts are made to mine through them.

Chapter 5

APPLICATIONS TO WATER QUALITY PROBLEMS

It should now be apparent that the rocks of the coal mining portion of the Southern Illinois 208 area vary from place to place both vertically and in a geographic sense. To say anything meaningful about the ability of the rocks to affect water quality on a regional basis, one must keep these differences in mind.

Most of the rocks in the Southern Illinois 208 area are clastic sedimentary rocks and as such are composed mainly of minerals that are only slightly soluble in pure water. Left unmolested, nature would weather and erode these rocks so slowly that water quality would remain good. Even if disturbed by mining, a rock composed only of the common clastic minerals such as quartz, clay minerals, etc., would not react fast enough to affect chemical quality of the water although it might affect the suspended load. Even the carbonate minerals in limestones would not by themselves dissolve rapidly enough to degrade water quality.

However, many of the rocks in this area contain a small percentage of pyrite, an iron sulfide mineral (FeS_2). Pyrite, unlike the major components of sedimentary rocks, reacts rapidly when exposed to oxygen and water to give acidic conditions. The following equations illustrate these oxidative weathering reactions.

1. $FeS_2 + 7/2\ O_2 + H_2O = Fe^{++} + 2SO_4^{=} + 2H^+$
2. $Fe^{++} + 1/4\ O_2 + H^+ = Fe^{+++} + 1/2\ H_2O$
3. $Fe^{+++} + 3H_2O = Fe(OH)_3 + 3H^+$

Equation 1 shows one mole of pyrite being oxidized in the presence of water and oxygen to give ferrous ions, sulfate ions, and two moles of hydrogen ions (acidity). Equation 2 shows how a ferrous ion can become oxidized to give a ferric ion. Ferric ions are not stable in the presence of water except under very acid conditions and react according to equation 3 to give ferric hydroxide and other ferric compounds, which

is the "yellowboy" of acid mine drainage. Because equation 2 uses up acidity and equation 3 generates it, the overall effect can be better seen by combining the two into a new equation:

4. $Fe^{++} + 5/2\ H_2O + 1/4\ O_2 = Fe(OH)_3 + 2H^+$

This equation shows that the oxidation of the ferrous ion and the subsequent precipitation of iron as ferric hydroxide generates a net amount of 2 moles of acidity. Thus the oxidation of the pyritic sulfide to sulfate generates two moles of acidity and the oxidation and precipitation of the pyritic ion generates another two moles, giving a total of four moles of acidity that are produced when one mole of pyrite oxidizes completely. The acidity and the sulfate ions can be considered together, and the oxidation products described as sulphuric acid, H_2SO_4.

It has been demonstrated that the ferric ion, although not usually present in large amounts, can act as a very strong oxidation agent to oxidize pyrite much more rapidly than just oxygen and water. The equation is:

5. $FeS_2 + 14Fe^{+++} + 8H_2O = 15Fe^{++} + 2SO_4^{=} + 16\ H^+$

At first glance it would seem that this reaction would produce 16 moles of acidity, but it must be remembered that to generate each mole of Fe^{+++} one mole of acidity must be used up (Equation 2). Thus, equation 5 shows a net gain of two moles of acidity to oxidize one mole of pyrite to ferrous ions and sulfate, the same amount as is shown in the oxidation of pyrite to these same materials via oxygen and water in equation 1.

We may also write an equation for the neutralization of the sulphuric acid. In the Southern Illinois 208 area, the most common neutralization material is limestone, which when pure has the formula $CaCO_3$. Thus, the equation for neutralization is:

6. $H_2SO_4 + CaCO_3 = Ca^{++} + SO_4^{=} + H_2CO_3$

If conditions are acidic, most of the H_2CO_3 (carbonic acid) itself will decompose.

7. $H_2CO_3 = H_2O + CO_2(gas)$

Thus, one mole of calcium carbonate is required to neutralize a mole of sulphuric acid. This can be expressed in different terms. If a rock contains one percent sulphur, and all the sulphur is contained in pyrite, it will take 31.25 tons of pure calcium carbonate (limestone) to completely neutralize the acid produced by the oxidative weathering of the pyrite in one thousand tons of the rock.

If the acid produced by weathering of pyrite is not neutralized by calcium carbonate, it can cause a variety of effects. Some of these are listed below.

1. The H^+ can act as an exchange ion, displacing ions such as sodium, potassium, and magnesium from clay minerals.

2. If present in great enough concentrations, the H^+ can dissolve the clay minerals themselves, releasing in the process the aluminum contained within the clay.

3. Manganese and iron coatings that are commonly present on clay minerals can be dissolved, releasing these elements to the water.

4. Various trace elements which may be present as exchange ions on clays or adsorbed on the manganese-iron coatings may be released to the water by the action of the H^+.

5. The mineral sphalerite is present in small amounts in some of the overburden rocks. This mineral is capable of slow oxidative weathering itself, but dissolves rather quickly in the presence of acid. This releases zinc to the water. Cadmium is commonly present in sphalerite, and acid attack releases this element as well.

Each of these processes uses up hydrogen ions and thus is a form of neutralization of the acid.

According to Equation 6, the neutralization of the sulphuric acid will release one calcium ion (Ca^{++}) for each sulfate ion. Thus for water that has had an appreciable amount of its acid neutralized, there should be an almost one to one ratio of calcium ions to sulfate ions. Water analyses commonly use the parameter "hardness" as a measure of calcium (plus the less common but related element, magnesium). Hardness is reported as the equivalent amount of calcium carbonate, i.e., one unit of hardness would correspond to one unit of calcium carbonate. Calcium carbonate has nearly the same atomic weight as sulfate, so there should be a one to one weight ratio of hardness to sulfate, i.e., if sulfate is 1000 ppm, hardness should be 1000 ppm also.

The rate at which the pyrite weathers will govern the overall sulfate concentration and hence the total amount of dissolved material in the water.

The Net Neutralization-pH Relationship

The net neutralization potential is a measure of the ability of a rock to either neutralize or produce acid. It is a number which indicates the tons of calcium carbonate per 1000 tons of rock that is either in excess of the amount needed to neutralize the sulphur present or the additional calcium carbonate that would have to be added to completely neutralize the sulphur present. It is calculated by subtracting the acid-producing potential from the neutralization potential; thus, rocks with calcium carbonate in excess of that needed to neutralize the sulphur will have positive values of net neutralization potential whereas those with sulphur in excess will have negative values. As an example, consider a rock unit that contains two percent calcium carbonate and one percent sulphur. The net neutralization potential would then be the neutralization potential (2% x 1000 ton = 20 tons $CaCO_3$) minus the acid potential (1% x 31.25 tons $CaCO_3$ needed to neutralize one percent sulphur). This gives a value of -11.3 for net neutralization potential. Expressed another way, 11.3 tons of calcium carbonate would have to be added to neutralize the sulphur in 1000 tons of the rock.

Mercier (1978) has measured the pH of water passed through columns of crushed overburden rocks whose net neutralization potential had been determined. The results, shown in Fig. 9, indicate that drainage water associated with rocks having net neutralization potentials greater than 50 tons $CaCO_3$/1000 tons of material will have pH values greater than 7. As the net neutralization potential falls toward zero, pH decreases to about 6.5. With net neutralization potential becoming negative (i.e., the rocks are potentially acidic), pH continues to fall to about pH 3 as net neutralization potential approaches -100. He also compared the net neutralization potential measured for overburden material from two mines in southern Illinois and one in western Kentucky to the pH of water draining the mines. The range in pH measured in these mines over a six-month period is given by the vertical lines on the graph. The pH of the water draining these spoils of known net neutralization potential compared closely with his experimental curve.

Mercier's graph suggests that a net neutralization potential of -18 would be sufficient to lower the pH to 6. Any value more negative than -18 would probably produce a water out of compliance with water quality standards which require that waters have a pH value of 6 to 9.

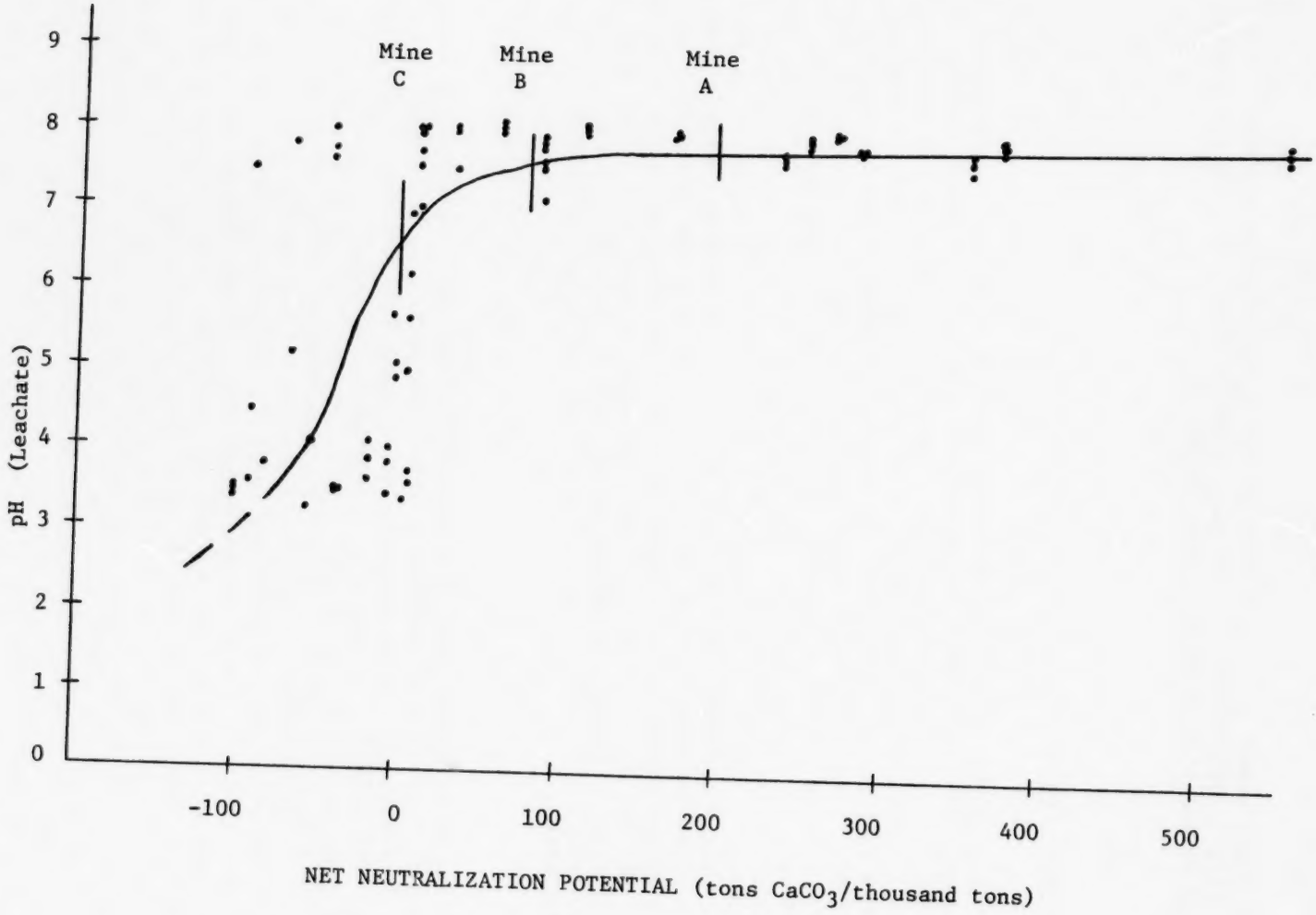

Figure 9. Experimentally established relationship between pH and net neutralization potential (after Mercier, 1978).

In other words, a value of 0.58 percent sulphur in overburden rocks, if unbalanced by limestone, would be likely to generate a water too acidic to meet environmental standards.

General Evaluation

A very general evaluation of overburden rock-water quality relations can be made from the overall composition of the various Pennsylvanian formations. Data for the overall composition of the various formations in Illinois is presented by Kosanke, et al. (1960), and is reproduced here as Fig. 10. From this, the amount of limestone can be approximated. Some simplifying assumptions must be made. It is assumed for the purpose of this discussion that the limestone indicated in Fig. 10 is pure limestone, and that the other lithologies of the formation contain no calcium carbonate. Neither of these is true; the limestones commonly contain large amounts of clay, reducing the amount of calcium carbonate contained in the rock. Shales and sandstones commonly contain calcium carbonate nodules and cements, increasing the total calclium carbonate content of the formation. These two features act in opposite directions and the result of the assumption is that they cancel each other out. Another assumption to be made is that the limestone is uniformly distributed, vertically and horizontally, throughout the formation.

Using these assumptions, one percent of limestone in a formation would amount to 10 tons of calcium carbonate per 1000 tons of overburden. This amount of calcium carbonate would neutralize the equivalent of 0.32 percent sulphur. By use of this approach, the amount of sulphur that can be neutralized can be calculated for each Pennsylvanian formation (Table 1). General estimates of sulphur content of the formations are not available; however, published and unpublished values of sulphur are available for the overburden of seven mines in the Southern Illinois 208 area (Table 2). These can be used to give a rough idea of the sulphur content of the Spoon and Carbondale formations. The neutralization and sulphur values can be used to calculate a crude net neutralization potential, which can then be compared with Fig. 9 to estimate the pH of the drainage water. These data suggest that the water running off the overburden of the Spoon Formation will generally be neutral to acidic whereas that originating on Carbondale Formation rocks will usually be alkaline.

The reader is cautioned that the estimated net neutralization potentials of Table 2 are developed to give a rough idea as to what range in NNP can be expected in the Spoon and Carbondale Formations and should not

Table 1
LIMESTONE CONTENT AND EQUIVALENT AMOUNT OF SULPHUR THAT CAN BE NEUTRALIZED IN PENNSYLVANIAN FORMATIONS OF ILLINOIS

Formation	Percent Limestone	Equivalent Percent Sulphur
Mattoon	6	1.9
Bond	12	3.8
Modesto	5	1.6
Carbondale	5	1.6
Spoon	1	0.3
Abbott	0	0.0
Caseyville	0	0.0

Limestone data from Kosanke, et al. (1960)

Table 2
AVERAGE SULPHUR VALUES AND ESTIMATED NET NEUTRALIZATION POTENTIAL FOR SOME SOUTHERN ILLINOIS 208 AREA MINES

Mine	Formation	%S	Amount of S that can be neutralized (From Table 1)	Estimated Net Neutralization Potential
Will Scarlet*	Spoon	0.91	0.3	-19
Eagle*	Spoon	0.30	0.3	0
Carbondale No. 1**	Spoon	0.51	0.3	-7
Burning Star No. 2 (Walker Pit)*	Carbondale	1.44	1.6	5
Burning Star No. 2 (DuQuoin Pit)*	Carbondale	0.29	1.6	41
Delta**	Carbondale	1.07	1.6	17
Captain**	Carbondale	1.79	1.6	-6
Ayshire**	Carbondale	0.81	1.6	25

*Source: Smith, et al., 1976

**Source: Hood, unpublished

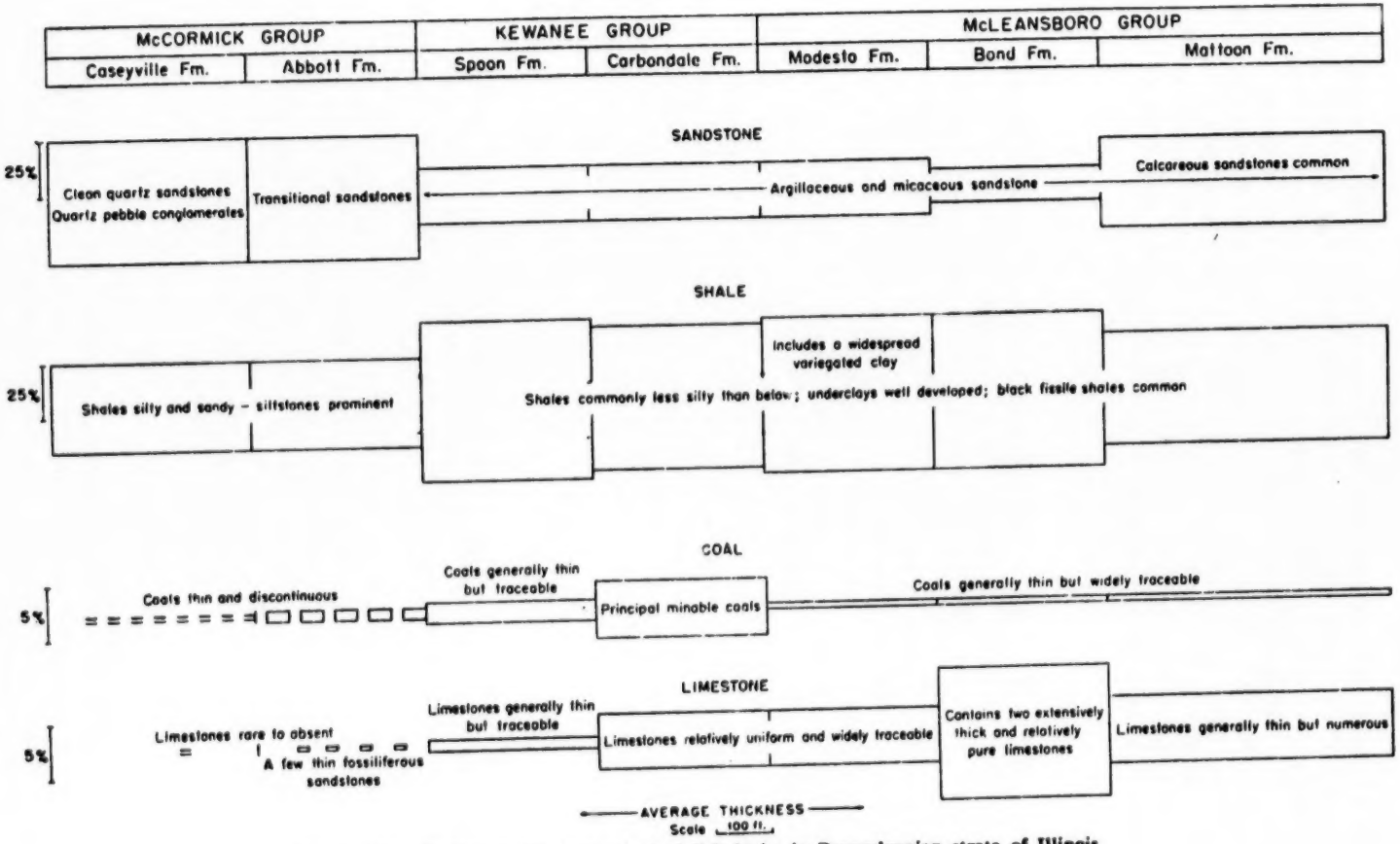

Fig. 4. — Distribution of the four principal lithologies in Pennsylvanian strata of Illinois.

Figure 10. Kosanke et al. (1960) estimation of the distribution of lithologies in Pennsylvanian formations of Illinois.

be construed as being the actual NNP for the individual mines themselves. Net neutralization potentials are available for the four mines examined by Smith, et al. (1976). These values are 24 for Will Scarlet, 13 for Eagle, 318 for Burning Star No. 2 - Walker, and an average of 242 for Burning Star No. 2 - DuQuoin. These numbers are all higher than the estimated values, some by considerable amounts. The discrepancy arises because rock types are not uniformly distributed in either a horizontal or vertical direction (one of the original assumptions) and that can greatly change the general picture at specific mines.

The two Burning Star No. 2 pits and the Captain Mine are all located west of the DuQuoin Monocline, where the Carbondale Formation is considerably richer than average in carbonate rocks. Data presented by Dutcher, et al. (1977), indicate there is about 16 percent limestone in the Burning Star No. 2 area, which would by itself raise the NNP values well above 100. In addition, some of the shales are limey, which would raise the values even more. A sulphur content as high as that in the Captain Mine should, in general, result in a negative NNP for the Carbondale Formation rocks. However, at the Captain Mine on the order of 25 percent of the overburden is limestone, which would raise the NNP at that mine to about 195. On the other hand, the Ayshire Mine mined the No. 5 Coal Member is an area well east of the DuQuoin Monocline. In the area of the mine, the St. David Limestone Member is only about a foot thick. This amounts to an estimated 2 percent of the highwall, and the estimated net neutralization potential would drop accordingly down to approximately -5.

In summary, the general evaluation suggests that mines in the Spoon Formation would tend to generate runoff that would have a pH of less than 7. The Carbondale Formation west of the DuQuoin Monocline ought to generate water with pH above 7. East of the monocline, the portion of the Carbondale Formation above the No. 6 Coal ought to produce runoff above pH 7, whereas that below this coal might well generate runoff having values below 7. Judging from the sulphur analyses of the various Pennsylvanian age rocks, it seems probable that the overburden above the Opdyke Coal in Jefferson County would not have more than 1.9 percent sulphur. Thus, drainage in this area would also be expected to remain above 7.

Because the Carbondale and Spoon Formations contain most of the mineable coals, the basins which contain the largest percentages of these formations are those that might ultimately be most affected by surface mining. Table 3 shows a breakdown of the percentage of various formations in each of the second order basins (GERPDC terminology) in the Southern

Table 3
PERCENT OF VARIOUS FORMATIONS IN THE SECOND ORDER BASINS
SOUTHERN ILLINOIS 208 COAL MINING AREA

Basin	Mississippian	Caseyville	Abbott	Spoon	Carbondale	Modesto	Bond	Mattoon
1.		0.9	4.0	13.7	21.3	50.7	9.4	
2.	7.6	59.6	27.2	5.6				
3.	8.9	11.5	4.5	9.9	6.3	14.4	42.1	2.3
4.				0.1	4.0	61.5	34.5	
5.							60.0	40.0
6.							21.8	78.2
7.							5.8	94.2
8.							100.0	
9.							100.0	
10.							100.0	
11.							100.0	
12.							100.0	
13.							100.0	
14.							100.0	
15.							100.0	
16.							100.0	
17.							52.0	48.0
18.							100.0	
19.							100.0	
20.							80.6	19.4
21.							29.5	70.5
22.							12.7	87.3
23.					87.9	12.1		
24.					24.9	6.8		
25.			41.0	27.4				
26.		5.5	80.6	13.9				
27.		6.5	63.3	30.2				
28.		90.6	9.4				6.0	94.0
29.							25.6	74.4
30.						16.7	63.1	20.2
31.					16.1	79.9	4.0	
32.					1.8	36.6	54.7	6.9
33.					26.1	53.1	20.8	
34.								
35.	0.2	0.8	41.7	41.1	16.4			

Table 3 (Cont'd)

Basin	Mississippian	Caseyville	Abbott	Spoon	Carbondale	Modesto	Bond	Mattoon
36.		1.0	1.5	1.4	8.7	79.7	7.6	
37.					14.9	7.4	77.7	
38.	4.6	0.9	2.6	17.3	58.6	15.8	0.3	
39.	0.4	20.4	25.3	21.4	28.0	4.5		
40.				20.6	79.4			
41.			5.5	68.1	26.4			
42.				8.8	91.3			
43.		34.2	54.9	10.9				
44.			100.0					

Illinois 208 area (Fig. 11). Those basins with large percentages of Spoon Formation, and those basins east of the DuQuoin Monocline which contain large percentages of the lower Carbondale Formation are the ones most likely to develop water quality problems if mining occurs. These basins are the ones needing the most care in reclamation to maintain water quality.

Lastly, it should be pointed out that the above analysis applies only to overburden rocks. In situations where the sulphur is concentrated, such as in gob piles and slurry ponds, the situation will be entirely different. In these areas, the net neutralization potential is likely to be quite negative and runoff correspondingly acidic.

In order to better evaluate the regional trends in net neutralization potential, approximately 60 drill logs were evaluated for this parameter. This was done by first collecting data on net neturalization potential for various kinds of overburden rocks in the Southern Illinois 208 area. The data are from Smith, et al. (1976), Mercier (1978), and unpublished data by the author. These were lumped into a few simplified rock types and the arithmetic mean value of net neutralization potential was calculated for each of the generalized rock types. These general values are tabulated in Table 4. Using these values, the drill logs were evaluated for overall net neutralization potential by weighting the net neturalization potential of each lithologic unit reported in the drill log by its thickness. The following equation shows how this was done:

$$\text{Overall NNP} = \frac{NNP_1 \times T_1 + NNP_2 \times T_2 + NNP_3 \times T_3 + \text{----} NNP_n \times T_n}{T_1 + T_2 + T_3 + \text{----} T_n}$$

where NNP is net neutralization potential, the subscripts refer to different lithologic units mentioned in the drill logs, and T is the thickness of each lithologic unit.

Many sources of error are possible using this approach. The lithologies were usually described by drillers rather than geologists, so matching terms was frequently a problem. Often parts of the drill hole were undescribed, especially the upper portion. These two factors made it impossible to use many drill logs. Another problem is that the drill holes obviously do not all go to the same depth. The evaluation was carried out to the bottom of the hole, or 150 feet, whichever was shallower.

Table 4
AVERAGE NET NEUTRALIZATION POTENTIAL OF SOME OVERBURDEN ROCKS IN THE SOUTHERN ILLINOIS 208 AREA

Lithology	No. of Samples	Mean Value (tons CaCO3/100 tons)
Pennsylvanian rocks		
Sandstone	19	+ 11
Limestone	31	+591
Shale (all types except carbonaceous)	19	+ 31
Shale, black fissile	20	- 67
Mudstone	48	+ 82
Underclay	6	+204
Surficial materials		
Loess	7	+ 32
Till	17	+ 7
Soil	5	+ 10
Correction factors		
"calcareous"		+200
"pyritic"		-100

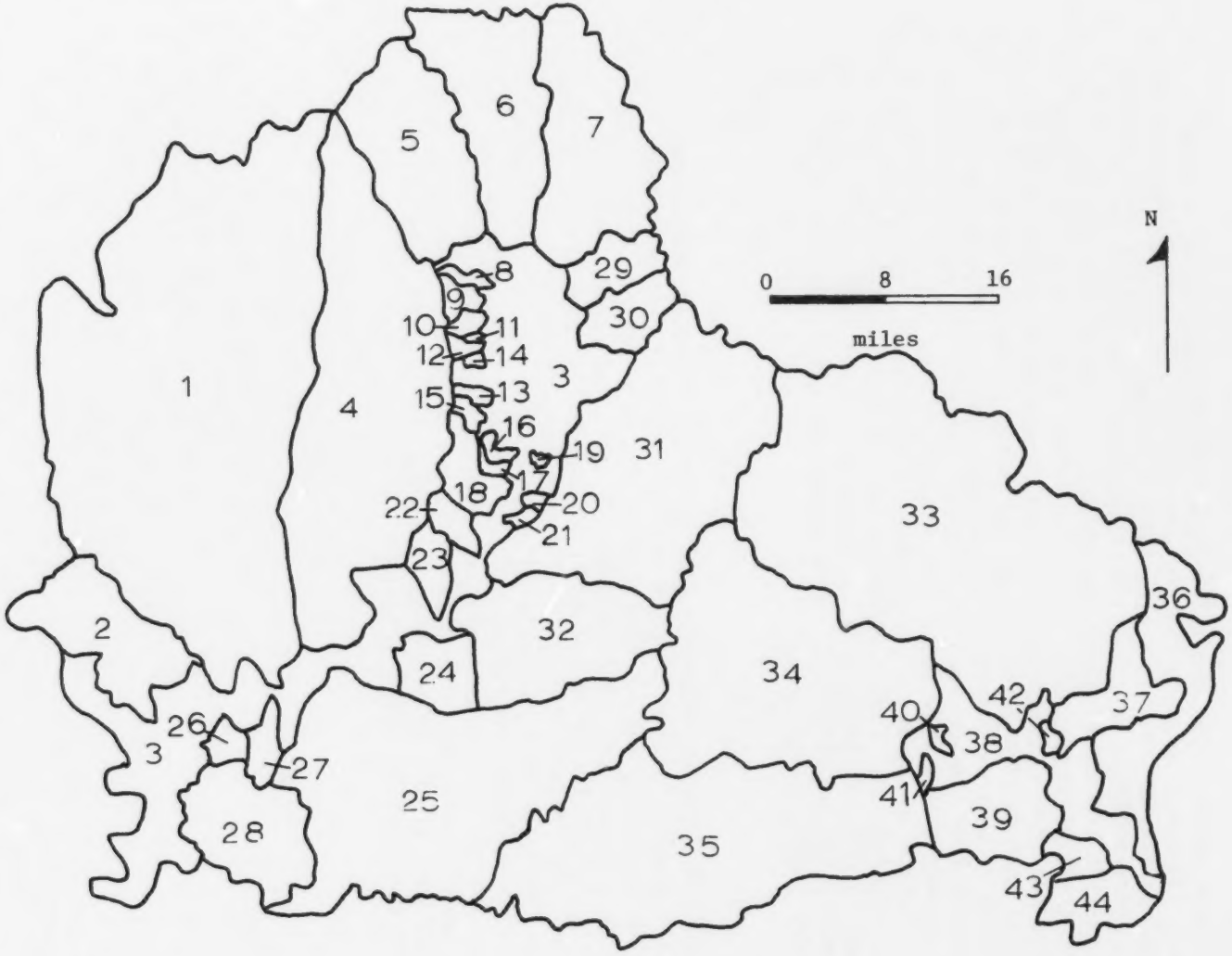

Figure 11. Second order basins of the Big Muddy and Saline River basins.

It is also obvious that the net neutralization potential of a given general lithology is going to vary considerably, depending upon what is in that particular rock at a particular locality. However, the average values were modified only when the adjectives "calcareous" or "pyritic" were used in the description. An arbitrary value of +200 was added to net neutralization potential of any lithology described as calcareous. This is the same as assuming a calcareous rock would contain about one-third as much calcium carbonate as the average limestone of the area. For units in which the word pyrite was mentioned, a value of 100 was subtracted from the net neutralization potential. The reasoning behind this assumes that a rock would need to contain five percent or more pyrite before the person logging the hole would notice it and mention it in the description. Five percent pyrite would be the equivalent of 2.7 percent sulphur, which in turn is equivalent to a little less than 90 in net neutralization potential. This number was simply rounded up to 100 for ease in calculation.

It should be apparent that this kind of data can provide only a very generalized picture of regional distribution of net neutralization potentials. Nevertheless, when plotted on a map,[1] the drill hole data appear to substantiate, in a very general way, the trends discussed earlier. Values for holes beginning in Caseyville rocks are higher than expected, and reflect limestones of the underlying Mississippian formations being included in the calculations. Data for holes beginning in the Spoon and Carbondale Formations show no significant differences between the two formations, which is somewhat surprising. Values for holes beginning in the Carbondale Formation show the difference in rocks east and west of the DuQuoin Monocline very well. Holes east of the structure average 37, those west 106.

[1]The map is not included in this report. Copies are available from GERPDC as "Second Order Basins of the Southern Illinois 208 Area."

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

Most of the commercially valuable coals in the Southern Illinois 208 area are in the Spoon and Carbondale Formations. The Spoon Formation and the lower part (below the No. 6 Coal) of the Carbondale Formation east of the DuQuoin Monocline appear to have limited net neutralization potentials and mining in areas including these rocks has the potential to produce acidic runoff. Water draining mines in the No. 6 Coal or mines west of the DuQuoin Monocline will probably contain enough carbonate rock to produce neutral to basic runoff, although the runoff might well be high in sulfate, hardness, and total dissolved solids.

It is recommended that net neutralization potentials be determined for overburden rocks in the planning stages of mine development and periodically during mining and that provision be made for rapid burial of any overburden rock with a negative net neutralization potential.

Mines in areas where the overall net neutralization potential of the overburden is negative may well find it difficult to meet environmental standards and probably should include a water treatment facility in their planning.

REFERENCES

Allgaier, G. J., and Hopkins, M. E., 1975, Reserves of the Herrin (No. 6) Coal in the Fairfield Basin in Southeastern Illinois: Illinois State Geological Survey Circular 489, 31 pp.

Baxter, J. W., Desborough, G. A., and Shaw, C. W., 1967, Areal geology of the Illinois fluorspar district. Part 3- Herod and Shelterville Quadrangles: Illinois State Geological Survey Circular 413, 41 pp.

Bristol, H. M., and Howard, R. H., 1971, Paleogeologic map of the Sub-Pennsylvanian Chesterian (Upper Mississippian) surface in the Illinois Basin: Illinois State Geological Survey Circular 458, 14 pp.

Cady, G. H., Lowenstam, H. A., Smith, H. L., Pullen, M. W., Rolley, M. B., and Siever, R., 1951, Subsurface geology and coal resources of the Pennsylvanian system in certain counties of the Illinois Basin: Illinois State Geological Survey R. I. 148, 274 pp.

Cote, W. E., Reinersten, D. L., and Killey, M. M, 1969, Geological science field trip: Equality area: Illinois State Geological Survey Guide Leaflet 1969A & F, 31 pp.

Dutcher, L. A., Dutcher, R. R., and Hopkins, M. E., 1977, Geology of southern Illinois coal deposits: in C. O. Frank, ed., Field Guide for the North Central GSA, Carbondale, 1977. Volume 2: Postmeeting Field Trips, p. 1-33. Department of Geology, Southern Illinois University, Carbondale.

English, R. M., and Grogan, R. M., 1948, Omaha Pool and mica peridotite intrusives, Gallatin County, Illinois: Illinois State Geological Survey R. I. 130, 23 pp.

Ethridge, F. G., and Fraunfelter, G., 1976, Variability within a high constructive lobate delta: The Pounds Sandstone of southeastern Illinois: Sixth Annual Field Conference, Great Lakes Section, Society of Economic Paleontologists and Mineralogists, Department of Geology, Southern Illinois University, Carbondale.

Ethridge, F. G., Fraunfelter, G., and Utgaard, J., 1973, Depositional environments of selected Lower Pennsylvanian and Upper Mississippian sequences of southern Illinois: Thirty-seventh Annual Tri-State Field Conference, Department of Geology, Southern Illinois University, Carbondale, 158 pp.

Frye, J. C., Leonard, A. B., Willman, H. B., and Glass, H. D., 1972, Geology and paleontology of Late Pleistocene Lake Saline, Southeastern Illinois: Illinois State Geological Survey Circular 471, 44 pp.

Preceding page blank

Givens, T., 1967, Paleoecology and environment of deposition of part of the Brereton and Jamestown Cyclothems (Middle Pennsylvanian) of Williamson County, Illinois: Unpublished M. S. Thesis, Southern Illinois University, Carbondale.

Grenda, J. C., 1969, Paleontology of two Middle Pennsylvanian black shales in the Brereton and St. David Cyclothems in parts of Jackson and Perry Counties, Illinois: Unpublished M. S. Thesis, Southern Illinois University, Carbondale.

Hopkins, M. E., 1968, Harrisburg (No. 5) Coal reserves of southeastern Illinois: Illinois State Geological Survey Circular 431, 25 pp.

Hopkins, M. E., and Simon, J. A., 1974, Coal resources of Illinois: Illinois State Geological Survey Mineral Note 53, 24 pp.

Illinois Nature Preserves Commission, 1973, Comprehensive plan for the Illinois Nature Preserves System. Part 2. The natural divisions of Illinois: Illinois Nature Preserves Commission, Rockford, Illinois. 32 pp.

Kosanke, R. M., Simon, J. A., Wanless, H. R., and Willman, H. B., 1960, Classification of the Pennsylvanian strata of Illinois: Illinois State Geological Survey R. I. 214, 84 pp.

Lamar, J. E., 1925, Geology and mineral resources of the Carbondale Quadrangle: Illinois State Geological Survey Bulletin 48, 172 pp.

Leighton, M. M., Ekblaw, G. E., and Horberg, C. L., 1948, Physiographic divisions of Illinois: Journal Geology, 56, 16-33.

Mercier, M. J., 1978, A chemical weathering study of overburden materials from three surface coal mines in southern Illinois and western Kentucky: Unpublished M. S. Thesis, Southern Illinois University, Carbondale, 111 pp.

Smith, R. M., Grube, W. E., Arkel, T., and Sobek, A., 1974, Mine spoil potential for soil and water quality: U.S. Environmental Protection Agency, EPA-670/2-74-070, 319 pp.

Smith R. M., Sobek, A. A., Arkel, T., Sencindiver, J. C., and Freeman, J. R., 1976, Extensive overburden potentials for soil and water quality: U.S. Environmental Protection Agency, EPA-600/2-76-184, 311 pp.

Smith , W. H., 1957, Strippable coal reserves of Illinois: Part 1. Gallatin, Hardin, Johnson, Pope, Saline and Williamson Counties: Illinois State Geological Survey Circular 228, 39 pp.

Smith, W. H., 1958, Strippable coal reserves of Illinois: Part 2. Jackson, Monroe, Perry, Randolph, and St. Clair Counties: Illinois State Geological Survey Circular 260, 35 pp.

Utgaard, J., and Givens, T., 1973, Middle Pennsylvanian depositional environments, Delta Mine, Williamson County, Illinois: in F. G. Ethridge, et al., eds., Guidebook to "Depositional environments of selected Lower Pennsylvanian and Upper Mississippian sequences of southern Illinois, P. 90-106. Department of Geology, Southern Illinois University, Carbondale.

Ward, C.R., 1977, Mineral matter in the Springfield-Harrisburg (No. 5) Coal Member in the Illinois Basin: Illinois State Geological Survey Circular 498, 35 pp.

Wetendorf, F., 1967, Environment of deposition of parts of the Brereton, Jamestown, and Bankston Cyclothems (Middle Pennsylvanian) of Wil liamson County, Illinois: Unpublished M. S. Thesis, Southern Illinois University, Carbondale.

Willman, H.B., Atherton, E., Bushbach, T. C., Collinson, C., Frye, J. C., Hopkins, M.E., Lineback, J.A., and Simon, J.A., 1975, Hand book of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, 261 pp.

Willman, H.B., and Frye, J.C., 1970, Pleistocene stratigraphy of Illinois: Illinois State Geological Survey Bulletin 94, 204 pp.

Wilson, G. M., 1959, Field trip to extreme southeastern Illinois: Illinois Geological Society, 15 pp.